Measurement of Low Amounts of Precipitable Water Vapor Using Ground-Based Millimeterwave Radiometry

PAUL E. RACETTE,[*] ED R. WESTWATER,[+] YONG HAN,[#] ALBIN J. GASIEWSKI,[@] MARIAN KLEIN,[+] DOMENICO CIMINI,[&] DAVID C. JONES,[**] WILL MANNING,[++] EDWARD J. KIM,[*] JAMES R. WANG,[*] VLADIMIR LEUSKI,[+] AND PETER KIEDRON[##]

[*]*NASA Goddard Space Flight Center, Greenbelt, Maryland*
[+]*Cooperative Institute for Research in Environmental Sciences, University of Colorado/NOAA/Environmental Technology Laboratory, Boulder, Colorado*
[#]*NOAA/National Environmental Satellite Data and Information Service, Silver Spring, Maryland*
[@]*NOAA/Environmental Technology Laboratory, Boulder, Colorado*
[&]*CETEMPS, University of L'Aquila, L'Aquila, Italy*
[**]*Met Office, Exeter, United Kingdom*
[++]*Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland*
[##]*Atmospheric Sciences Research Center, The University at Albany, State University of New York, Albany, New York*

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ABSTRACT

Extremely dry conditions characterized by amounts of precipitable water vapor (PWV) as low as 1–2 mm commonly occur in high-latitude regions during the winter months. While such dry atmospheres carry only a few percent of the latent heat energy compared to tropical atmospheres, the effects of low vapor amounts on the polar radiation budget—both directly through modulation of longwave radiation and indirectly through the formation of clouds—are considerable. Accurate measurements of PWV during such dry conditions are needed to improve polar radiation models for use in understanding and predicting change in the climatically sensitive polar regions. To this end, the strong water-vapor absorption line at 183.310 GHz provides a unique means of measuring low amounts of PWV. Weighting function analysis, forward model calculations based upon a 7-yr radiosonde dataset, and retrieval simulations consistently predict that radiometric measurements made using several millimeter-wavelength (MMW) channels near the 183-GHz line, together with established microwave (MW) measurements near the 22.235-GHz water-vapor line and ~31-GHz atmospheric absorption window can be used to determine within 5% uncertainty the full range of PWV expected in the Arctic. This combined capability stands in spite of accuracy limitations stemming from uncertainties due to the sensitivity of the vertical distribution of temperature and water vapor at MMW channels.

In this study the potential of MMW radiometry using the 183-GHz line for measuring low amounts of PWV is demonstrated both theoretically and experimentally. The study uses data obtained during March 1999 as part of an experiment conducted at the Department of Energy's Cloud and Radiation Testbed (CART) site near Barrow, Alaska. Several radiometers from both NOAA and NASA were deployed during the experiment to provide the first combined MMW and MW ground-based dataset during dry Arctic conditions. Single-channel retrievals of PWV were performed using the MW and MMW data. Discrepancies in the retrieved values were found to be consistent with differences observed between measured brightness temperatures (TBs) and forward-modeled TBs based on concurrent radiosonde profiles. These discrepancies are greater than can be explained by radiometer measurement error alone; errors in the absorption models and uncertainty in the radiosonde measurements contribute to the discrepancies observed. The measurements, retrieval technique, and line model discrepancies are discussed, along with difficulties and potential of MMW/MW PWV measurement.

1. Introduction

The polar regions are an important but ill-understood component of the global climate system. In response to the need for improved understanding of the effect of the polar regions on global climate, the Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program established a climate observation site on the North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) in 1997 (Stamnes et al. 1999; Stokes and Schwartz 1994; Ackerman and Stokes 2003). The establishment of this site followed the year-long Surface Heat and Energy Budget of the Arctic (SHEBA) study (Curry et al. 2000); many similar instruments deployed during SHEBA are deployed at the NSA/AAO Cloud and Radiation Testbed (CART) site. Many of the important scientific questions associated with the Arctic region are discussed by Stamnes et al. (1999) and by Curry et al. (1996). These studies have shown that water vapor and clouds play an essential role in moderating earth's climate and that accurate measurements of the atmospheric water distribution are needed to adequately model earth's radiation budget. In our work, we focus on the difficult problem of measuring precipitable water vapor during cold and dry conditions.

Corresponding author address: Paul Racette, NASA GSFC, Mail Code 555, Greenbelt, MD 20771.
E-mail: Paul.E.Racette@nasa.gov

5. Summary and conclusions

Accurate measurement of water vapor during dry conditions is important for modeling the radiation budget in polar regions. Based on a history of radiosondes launched by the National Weather Service (NWS) at Barrow, Alaska, we found that dry conditions at Barrow are prevalent over a substantial fraction of the year. A probability distribution of PWV constructed using these radiosondes shows that there is a high percentage of cases (~50%) in which PWV is less than 5 mm—that is, those cases in which 183-GHz radiometry is promising. In this paper we evaluated theoretically the potential of MMW radiometry for measuring low amounts of PWV, presented experimental data, and pointed out the difficulties associated with such measurements.

Weighting function analysis shows the greatly enhanced sensitivity of the 183-GHz region to water vapor at low concentrations (PWV $<$ 5 mm); at higher concentrations (PWV $>$ 10 mm), the sensitivity of measurements made using the 23- and 31-GHz channels is adequate to retrieve PWV to better than 5% uncertainty. A combination of MW and MMW measurements yields adequate sensitivity over the entire range of PWV expected in the polar regions. The weighting functions near the 183-GHz channels, especially for PWV $>$ 2 mm, show a nonnegligible dependence on temperature. The use of either RAOBs or 60-GHz radiometer temperature-profile measurements improves the accuracy of the 183-GHz retrievals. We have described a flexible retrieval algorithm for LWP and PWV from ground-based measurements. Using a collection of representative atmospheric profiles, we have simulated the expected retrieval performance of various channel combinations for conditions that are experienced at higher latitudes. The results show, that in the absence of ice cloud, a combination of channels from 23 to 183 GHz can yield very accurate estimates (uncertainties <5%) of PWV in very dry to moist atmospheres. These results are consistent with the weighting function analysis. This study indicates that the channels centered about the 183-GHz absorption line together with the existing MWR channels could provide complete measurement coverage for all of the PWV conditions encountered at Barrow.

The NASA GSFC and NOAA/ETL deployed a suite of radiometers covering the spectral range from 20 to 340 GHz. High-quality radiometric measurements were made over a 23-day period between 7 March and 30 March 1999. Two radiometer systems with redundant channels were independently calibrated. The NOAA/ETL radiometer used the tip-cal technique, while the NASA GSFC MIR system used hot and ambient calibration references to achieve calibration, with the exception of the 89- and 150-GHz channels, which used the tip-cal. Data from the redundant channels were in basic agreement.

Several very cold, dry, and clear days have been analyzed and, on a daily basis, these data show substantial fluctuations in the MMW brightness temperatures (some 25–30 K), while corresponding variations in the ARM MWR were less than 0.5 K. During cloud-free conditions observed over the experiment, the range of TB variations for the MWR was 3.5 K; over the same interval, the range of TB from the 183 $\pm$ 7 GHz channel was 70 K.

Initial PWV comparisons derived from MMW measurements and from measurements made by the two MWR systems showed large discrepancies. Upon closer examination, the discrepancies were attributed to calibration errors in the MWR, some as large as 2 K. Application of the Han and Westwater (2000) calibration algorithm for the MWR yielded much better agreement between the MWR and MMW PWV measurements.

Comparisons of contemporary absorption models show that substantial differences exist among them. The differences in these absorption models represent a substantial fraction of the error in retrieved PWV values. Determining an adequate model will provide substantial benefit to remote sensing by MMW radiometry. Comparisons of forward-modeled brightness temperature calculations based on radiosonde profiles and radiometer measurements show significant differences. For the MWR channels, the Liebe et al. (1993) model agreed best with the measurements with better than 0.1 K bias and a standard deviation of better than 0.2-K root-mean-square. However, for the MMW channels, the Liebe et al. (1993) model significantly over predicted TB. The uncertainties in RAOB measurements of water vapor, coupled with MIR and CSR calibration uncertainties of ~3 K, did not allow us to make a clear choice between the Liebe and Layton (1987) and the Rosenkranz (1998) absorption models. The observed differences could be due to uncertainty in radiosonde data, absorption models, radiometer calibration or, most likely, a combination of these. The largest differences observed were between measurements and calculations at the 183 $\pm$ 1 and $\pm$ 3 channels. We showed that at least some of these differences could be explained by incorrect radiosonde measurements of water vapor in the upper troposphere and lower stratosphere.

Single-channel and multichannel retrievals were performed using a combination of MW and MMW data. Differences as large as 50%–100% in the retrieved PWV values are consistent with differences observed in the forward-model TB comparisons. These differences are attributed to errors in the absorption model, errors in the background temperature field and radiometer calibration. Additional measurements and further refinement of experimental design are needed to quantify the error sources. Emphasis should be placed on reducing the uncertainty of the radiometer measurements and improving the quality and quantity of radiosonde launches at the experiment site. An examination of the accuracies of the absorption models in the context

Overall, the study shows that using 183-GHz radiometers to improve MWR retrievals at low amounts of PWV is sound, with a roughly 25-fold increase in dynamic range during very dry conditions. A variety of simulations and theoretical considerations all suggest that better than 5% percent accuracy can be obtained during clear conditions for the range of PWV expected in the polar regions. However, retrieval of PWV using MMW radiometric measurements is complicated by absorption model uncertainties as well as uncertainties in the radiometric measurements and background field.

Zenith brightness temperatures collected during the intensive observation period along with data documentation are available on the ARM archive (online at www.arm.gov).